

## **Geoacoustic Inversion in Shallow Water**

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### **LONG-TERM GOALS**

The ability to predict the sound field in shallow water environments depends to a large degree on having adequate knowledge of the geoacoustic properties of the bottom. The long term objectives of this research project are related to the investigation of experimental methods and inversion techniques for estimating parameters of geoacoustic models of the ocean bottom and the associated uncertainties in the model parameter values. The specific goals are to evaluate the performance of geoacoustic inversion techniques that have been developed for use in estimating geoacoustic model parameters in range-dependent shallow water environments, from an analysis of the results obtained for characterizing the seabed from the SW06 and other recent experiments. The wider context of this research is to achieve improved sonar system performance through greater understanding of the physics of the interaction of sound with the ocean bottom.

### **OBJECTIVES**

There are two objectives described in this research report.

- Performance comparison of geoacoustic inversion methods that have been developed for estimating geoacoustic models from acoustic field data. Inversion methods for estimating geoacoustic model parameters from acoustic field data have been developed over the past two decades. These include linearized approaches that make use of horizontal wave number data and travel time data; and nonlinear methods using time-frequency data, bottom loss data, and full field inversions based on matched field processing. Benchmarking workshops with simulated shallow water data have shown that the inversion methods are generally capable of estimating sound speed profiles in the bottom sediment materials (Tolstoy et al., 1998; Chapman et al., 2003). However, there has not been a benchmark comparison of inversion performance with experimental data. This leaves open the question of whether the inversion techniques can provide realistic estimates of geoacoustic model parameters, particularly the attenuation of sound in marine sediments.

The working hypothesis of this research is that the Shallow Water 06 (SW06) experiment provides an experimental benchmark for assessing the performance of geoacoustic inversion methods. The challenge is to synthesize the results obtained from the various inversion

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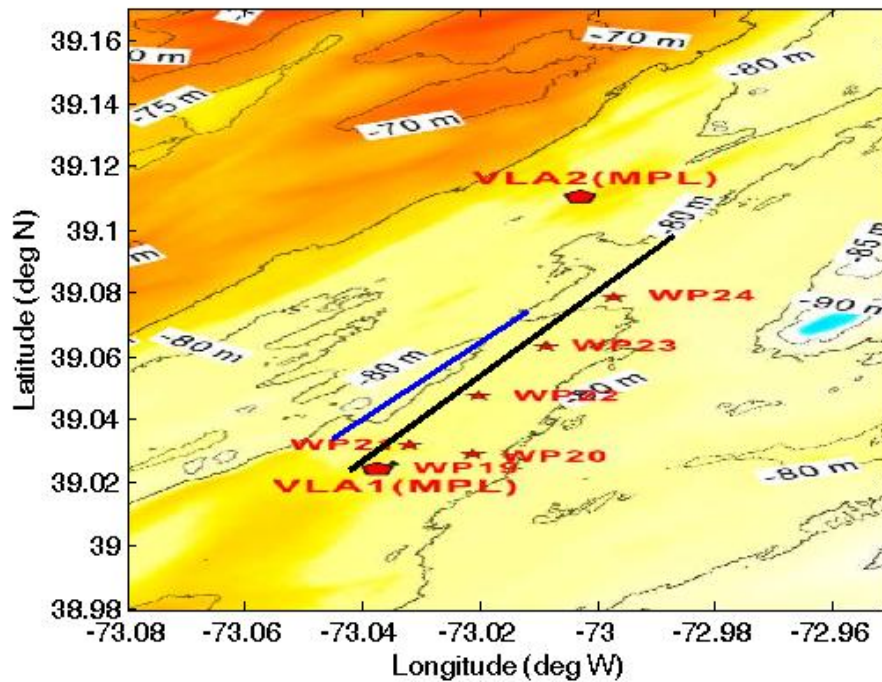
methods that were applied to data from the experiment, and develop and apply criteria for evaluating the inversion performance in estimating critical geoacoustic model parameters.

- An additional objective involves the continued analysis of SW06 data to develop a reliable inversion technique for estimating attenuation and sound speed dispersion in sediment over the frequency band from 100 – 4500 Hz where the frequency dependence in this band is expected to be non linear.

## APPROACH

Several experiments in SW06 were designed to provide data along tracks within a well ground-truthed region in the vicinity of the Applied Physical Laboratory (APL/UW) MORAY vertical array site, one of the central sites of the experiment (Figure 1). The experiments included:

- Matched field inversion (MFI) from continuous wave (CW) data (Jiang and Chapman, 2008; 2009 [*red stars in Figure 1*]); (Huang et al., 2008 [*red stars in Figure 1*])
- Inversion of bottom reflection waveform data (Choi et al. 2008 [*VLA1 site in Figure 1*]);
- Inversion of bottom loss versus angle data (Yang et al, 2012 [*VLA1 site in Figure 1*]);
- Linearized inversion of modal wave number data (Ballard et al., 2010 [*blue track in Figure 1*]);
- Linearized inversion of travel time data (Jiang and Chapman, 2010 [*VLA1 site in Figure 1*]).



**Figure 1. Location of the SW06 experiments on the New Jersey Shelf. The red square is the MORAY array site. The red stars follow the tracks of the MFI experiments, and the blue line nearly parallel to it follows the track of the wavenumber inversion experiment. The DRDC-A track with the 1200-Hz source is shown by the black line.**

The experiments provided high quality data over a frequency band from 100 – 4000 Hz that were used in inversions with various different approaches. Estimates of specific geoacoustic model parameters and the overall profiles from these experiments were collected and compared as a first level assessment of inversion performance. The geoacoustic profiles were then used to estimate transmission loss (TL) for comparison with data from a track towed in DRDC-A experiments with a sound source frequency of 1200 Hz in the mid-frequency band (Pecknold et al., 2008 [black line in Figure 1]).

Data from in situ probes, physical samples and high resolution chirp sonar surveys before and during SW06 provided the benchmark ground truth information. The chirp sonar surveys revealed well-resolved sub-bottom structure down to about 30 m, most prominently the ‘R’ reflector at about 20 m (Goff et al., 2004). This interface, which is pervasive in the region, was overlaid with alternating layers of sand and finer clay. The preliminary analysis of the situ sediment probe data indicated a sound speed value of around 1620 m/s for the sea floor sediments near VLA1 (Yang et al., 2008).

A novel signal processing technique for analysis of time-frequency information was applied to data from a broadband light bulb sound source deployed in the same region. The method involves ‘warping’ the initial time-frequency domain to a new domain in which the modal dispersion relationships are single tones. Warping is insensitive to the uncertainty in the experimental geometry (i.e. the source range) and enables resolution of the propagating modes at relatively short ranges. In previous work, the resolved modes were used as data in an inversion of the modal dispersion relationship to obtain estimates of the sediment sound speed and density (Bonnell and Chapman, 2012). The hypothesis in this research is that inversion can be carried out directly in the warped domain to obtain estimates of sound speed and attenuation in the sediment.

## **WORK COMPLETED**

The inter-model comparisons and the comparison with measured transmission loss were carried out using the geoacoustic profiles that were reported for each of the inversion methods that were used. The report shows the performance comparison of the following inversion methods:

- Waveform and bottom loss matching (Choi et al. 2008)
- Matched field inversion (Jiang and Chapman, 2008; 2009)
- Matched field inversion (Huang et al., 2008)
- Modal wavenumber inversion (Ballard et al., 2010).

The first method used data from the mid-frequency band (2-6 kHz), whereas the other three used low frequency data in the band 50-700 Hz). These methods were selected because they used data exclusively from the vicinity of the MORAY site where the ground truth was very well established.

The model predictions were done using the normal mode method (ORCA) and a sound speed profile measured by DRDC-A during the experiment. A range independent environment was assumed. This was a reasonable assumption given that the bathymetry was slowly varying over a large area in the vicinity of the site, and along the experimental track (less than 3 m over 12 km, Pecknold et al., 2008).

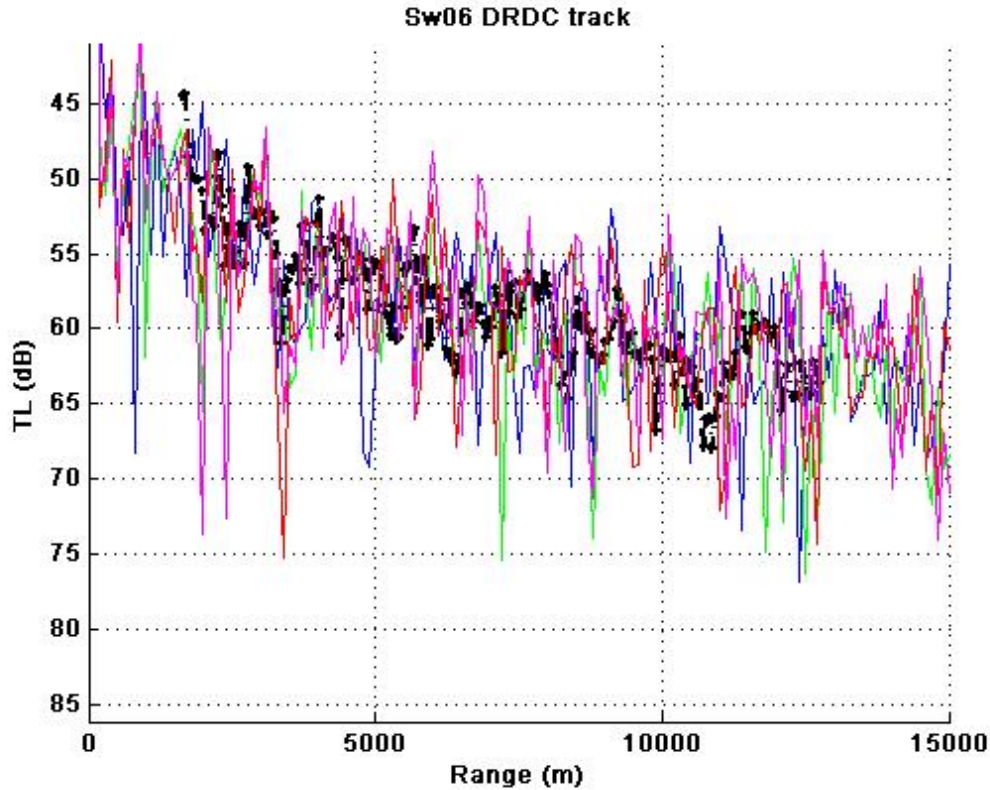
A technique that shows considerable promise for robust inversion with limited knowledge of the experimental environment is time-frequency warping. Time warping involves transforming the modal

dispersion relationship to a new time-frequency domain where the modes are represented as tones. This method was implemented and tested using light bulb data recorded on the MPL vertical array (Bonnell et al., 2012). The approach involved transforming the resolved modes in the warped domain back into the original time-frequency domain to carry out the inversion. In this work, theory was developed to enable the inversion directly in the warped domain, and simulations were carried out to test the approach.

## RESULTS

The comparison of sediment sound speed estimates against ground truth data showed that all the inversion methods provided results that were consistent with the chirp sonar survey and physical sample data. The details of the estimated geoacoustic profiles differed, and inter-model comparisons showed that the main features likely to affect the predictions of transmission loss are the average sound speed in the sediment layer and the layer thickness. The estimated sound speeds varied from 1600-1650 m/s (ratio of sediment to water bottom sound speeds  $\sim 1.07$ -1.1).

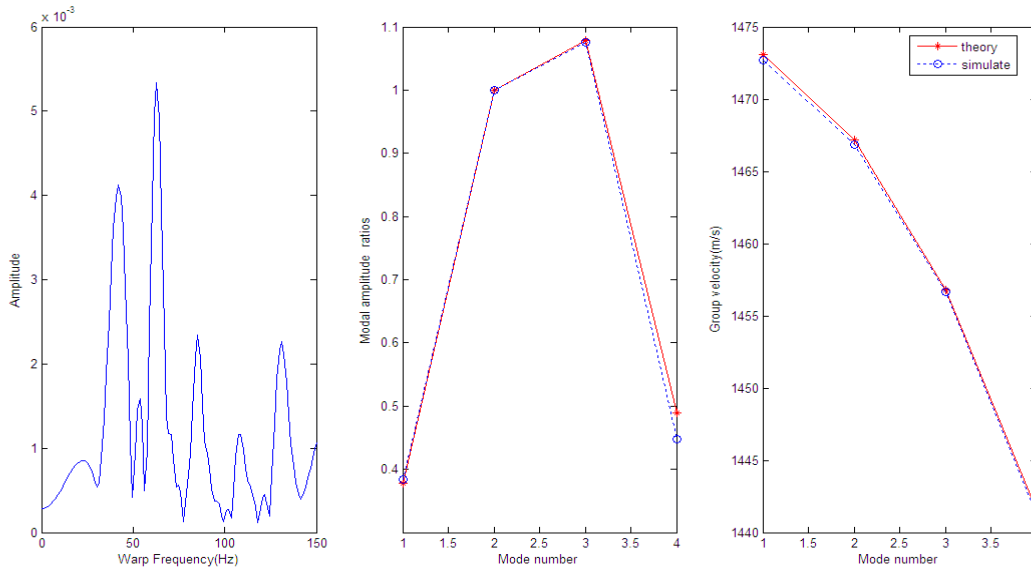
The predicted TL versus range from all the estimated geoacoustic models was very close over the range to 15 km. At low frequencies ( $F < \sim 400$  Hz) the range-averaged TL was similar for all models, indicating that the average sound speed in the sediment layer was similar; however, the spacing of peaks and nulls was sensitive to the estimated values of sediment layer thickness for each inversion method. At higher frequencies, the average loss was also similar for all the estimated profiles, and the predicted TL was in reasonable agreement with the experimental data over the short range out to 10-12 km (Figure 2). This is consistent with the result from Pecknold et al. (2008) that indicated low sensitivity to the sediment sound speed in the mid frequency band ( $\sim 1$  kHz).



**Figure 2.** Comparison of measured TL at 1200 Hz (black +) and modeled TL from Jiang and Chapman (blue); Huang et al. (red); Ballard et al. (green); and Choi et al. (magenta).

Values of attenuation estimates from the low frequency experiments varied from 0.05 dB/ $\lambda$  to 0.5 dB/ $\lambda$ . None of the estimated values was similar to the result from Dedui et al. (2007) who obtained a frequency dependent form for attenuation ( $\alpha(f) = \alpha_0 (f/f_0)^\beta$  with  $\alpha_0 \sim 0.34$  and  $\beta \sim 1.8$ ) from previous work in the New Jersey shelf region. The only estimates of attenuation were derived from mid-frequency (2-4 kHz) spectral ratio analysis of subbottom reflections from the R-reflector, and the values were again inconsistent (lower) with the result from Dedui et al. (2007). Although the inversion methods were very successful in estimating sound speed profiles, none was able to estimate attenuation in the sediment with reasonable uncertainty.

Initial investigation showed promising results for inverting attenuation at low frequencies from modal amplitude ratios of the time-warped signal. Simulations carried out for broad band data in a Pekeris shallow water environment showed that the modal amplitude ratio is preserved in the warped domain (Figure 3). Sediment attenuation can be estimated from the modal amplitude ratios, using values of sediment sound speed and density from inversion of the time-frequency dispersion.



**Figure 3. Left panel: Spectrum of time-warped signal; Middle panel: modal amplitude ratio from warped spectral data; Right panel: modal group velocity obtained from warped spectrum. The red symbols are the theoretical values, and the blue symbols are values obtained from the warped spectrum.**

## IMPACT/APPLICATIONS

The results indicate that data from the SW06 experiment provide an experimental benchmark for assessing the performance of geoacoustic inversion methods. The analysis showed that all the inversion methods were able to predict sound speed profiles that could adequately predict transmission loss at short ranges ( $< 15$  km). However, none of the methods designed for inversion of low frequency data was significantly sensitive to sediment attenuation, and so, cannot provide adequate estimates.

Inversion of mode amplitude ratios obtained by time-warping of broadband data is a promising technique for estimating attenuation. The method is insensitive to exact knowledge of the experimental geometry and sound speed in the water, and can provide high resolution modal data at relatively short ranges.

## **RELATED PROJECTS**

The data from the SW06 experiments are high quality data that can serve as benchmark standards for evaluating the performance of geoacoustic inversion methods to provide new understanding of the strengths and limitations of present day inversion techniques. The knowledge gained in this work will identify gaps in our understanding that can be addressed in designing the next phase of experiments. The research is connected with research projects of the following: W. S. Hodgkiss and P. Gerstoft (MPL, SCRIPPS); D. Knobles (ARL:UT); G.V. Frisk (Florida Atlantic); K. Becker (ARL Penn State); P. Dahl and D.J. Tang (APL UW); J. Miller and Gopu Potty (University of Rhode Island), J. Goff (U of Texas at Austin) and J. Lynch (WHOI). The overall goal of this group is to characterize the geoacoustic environment and understand mechanisms of the interaction of sound with the ocean bottom.

A secondary site in the SW06 experiment that was characterized by a top thin layer of medium sand was studied by several PIs (Knobles; Potty and Miller; Goff). This site was also surveyed extensively for ground truth, and can serve as another benchmark site

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